Neutrino Oscillation Appearance Experiment using Nuclear Emulsion and Magnetized Iron

D.A.Harris [a,b] , A. Para [b]

[a] *University of Rochester, Rochester, NY 14853*

[b] *Fermi National Accelerator Lab, Batavia, IL 60510*

Abstract

This report describes an apparatus that could be used to measure both the identity and charge of an outgoing lepton in a charged current neutrino interaction. This capability in a massive detector would allow the most comprehensive set of neutrino oscillation physics measurements. By measuring the six observable transitions between initial and final state neutrinos, one would be able to measure all elements of the neutrino mixing matrix, as well as search for CP violation, and matter effects. If the measured matrix is not unitary, then one would also have an unambiguous determination of sterile neutrinos. Emulsion is considered as the tracking medium, and different techniques are discussed for the application of a magnetic field.

1 Introduction

To observe all of the possible neutrino oscillation phenomena one would ideally ask for pure neutrino beams of different flavors, and a detector which could identify the three possible leptons in the final state of a charged current interaction. Traditional neutrino beams contain predominantly ν_μ or $\overline{\nu}_\mu$ with a small admixture of other neutrino flavors. Muon storage rings offer a possibility of mixed $\overline{\nu}_\mu/\nu_e$ and $\nu_\mu/\overline{\nu}_e$ beams. These beams will have virtually no admixture of other neutrino flavors, but they will contain neutrinos and antineutrinos. To exploit fully these beams and uniquely identify the oscillation mode one needs a determination of the electric charge of the outgoing lepton. This will uniquely distinguish neutrino from antineutrino interactions.

Several massive detectors exist which can identify the presence and charge of an outgoing muon, and some have been proposed to detect the presence of an outgoing tau or electron. However, measuring both the presence AND the charge of an outgoing tau, or electron, on an event-by-event basis remains a serious challenge in the field of neutrino oscillation experiments. Such a

measurement is necessary to detect a $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation in the presence of a ν_e component of the beam and/or to distinguish $\nu_\mu \rightarrow \nu_\tau$ from $\overline{\nu}_e \rightarrow \overline{\nu}_\tau$ oscillations. Precise measurements of $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\tau$ oscillation amplitudes would allow a test of unitarity of the neutrino oscillation mixing matrix, and an indirect search for sterile neutrinos. A measurement of the difference between $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ oscillation amplitudes could provide a direct test of T (or CP) violation, free of matter effects which affect a $\nu_e \rightarrow \nu_\mu$ and $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$ comparison.

In this paper we describe a detector which combines emulsion technology with a magnetic field. High resolution tracking capabilities of nuclear emulsions permit unambiguous detection of produced τ leptons and electrons, whereas a measurement of the deflection in a magnetic field allows a determination of the sign of the electric charge.

2 Lepton Identification in the Emulsion Detector

The CHORUS experiment has demonstrated the capabilities for identification of τ leptons through observation of its decay kinks in emulsion, and has set the most stringent limits on $\nu_\mu \rightarrow \nu_\tau$ at high δm^2 (1) to date. CHORUS uses a bulk nuclear emulsion as a detector; such a technique is prohibitively expensive for very large mass detectors.

A different geometry which is being studied by both the MINOS and OPERA collaborations involves interspacing emulsion plates, used as detectors, with thin lead plates, used as a target(2)(3). This geometry was used succesfully in studies of cosmic rays by the JACEE collaboration(4). Electronic tracking devices, sampling the emulsion detector with frequency of the order of $0.5\lambda_I$ are used to trigger the detector and to locate the interaction point to a small volume. That small volume can be removed from the detector and analyzed in nearly real time, with electronic tracking information serving as a guide to the analysis of the emulsion sheets.

An emulsion detector optimized for tau detection typically involves a thin lead plate serving as a target, followed by a a gap with two emulsion layers separated by a low-Z-material spacer. Track segments and their spatial angles are measured in both emulsion layers. Tau decays inside the spacer material are characterized by a large angle (typically above $50mrad$) between the downstream and upstream track segments. A certain fraction of taus decaying in the target plate can be identified by a large impact parameter of the resulting tau daughter.

Electromagnetic showers are sampled in emulsion with a typical granularity

of the order of $0.2X_0$. Thanks to the excellent spatial resolution of the emulsion and a high sampling frequency of the electromagnetic shower, individual acts of photon emission and conversion are easily detectable in the emulsion. Additional information is provided by the double ionization (measured via grain density along the track) of the electron-positron pair from a photon conversion.

An electron can be thus identified as a charged track with several conversion pairs within a small cone around it. An important feature of the emulsion detector is its ability to follow the initial electron track even inside the electromagnetic cascade.

3 Lepton Charge Determination

The electric charge of the particles can be determined by measuring the trajectory of a particles in the magnetic field. The simplest solution consists of replacing the lead target plates by iron ones and using an external coil to create a magnetic field in the iron in excess of $1Tesla$.

Charged particles traversing the iron plate will receive a p_t kick of $0.003xBGeV$, where x is the thickness of the steel plate in cm and B is the magnetic field in $Tesla$. At the same time, however, multiple scattering in the iron will generate a random pt of $0.014GeV\sqrt{\frac{x}{X_0}}$, where $X_0 = 1.76cm$ is the radiation length of steel. For a typical field strength of $1Tesla$, the multiple scattering effects dominate over the bending in the magnetic field. The situation improves when several iron plates are traversed: the p_t due to the magnetic field add linearly, whereas the multiple scattering induced p_t grows like $\sqrt{x}$. After a traversal of N steel plates with thickness x each, the significance of the charge determination is

$$\sigma = 2\frac{0.003B(Tesla)x(cm)}{0.014\sqrt{\frac{x}{X_0}}}\sqrt{N} \tag{1}$$

The factor of 2 accounts for the fact that we are not trying to determine the sign as such, but rather to distinguish between a positive and negative track hypothesis.

For a typical example of a detector with $x = 1mm$ $(0.05X_0)$ of steel, in a $1Tesla$ field, it takes about 100 planes or $10cm$ of iron to achieve a 2 σ sigma sign measurement. For muons, or even daughters of tau leptons it should be possible to achieve 3 or 4σ sign determination. In the electron case it may become impractical to follow the primary electron beyond some $5 - 10X_0$, however.

In case a more precise charge determination is required for electrons, the solution could be to immerse the entire detector in an external, strong magnetic field. In such a case a significant improvement of the measurement is achieved, as the space between the steel plates contributes to the magnetic bending as well, whereas its contribution to the multiple scattering is negligible in comparison with that of the iron plates.

As an example, consider a detector with $x = 1mm$ steel plates and a $2mm$ gap between them, immersed in $4Tesla$ magnetic field: it will require only $4 - 5$ emulsion plates to achieve a 5σ charge measurement.

Such a detector is not an impractical one: a 1 kton detector would have a total volume of $375m^3$ ($5m \times 5m \times 15m$). This is a rather modest volume in comparison, for example, with the ATLAS barrel toroidal magnet system(5), which generates a magnetic field of $2.4-4.2Tesla$ in a total volume of $7600m^3$. The ultimate size of a possible detector will be, thus, limited by the available resources, rather than by technical factors. A cost of a hypothetical detector with 20 kton of active mass would be of the order of 1100 million SF: 100 MSF for the superconducting magnet and 1000 MSF for the emulsion detector.

4 Conclusion

We have presented a concept of a novel detector involving large volume emulsion detectors interspaced with thin layers of steel. Such a detector should be capable of identification of the final state lepton (muon, electron or tau) with good efficiency and very small background. The superb spatial resolution and granularity of nuclear emulsions makes it possible to determine the sign of the electric charge of the lepton, once the detector is immersed in the magnetic field. The magnetic field can be generated by the excitation of steel plates with an external coil, or by immersion of the entire detector inside a superconducting magnet, similar to the ones being built for the LHC experiments.

With such a detector one can take full advantage of the physics opportunities provided by intense neutrino beams produced at a muon storage ring. It will allow a precise determination of the neutrino mixing matrix elements, search for matter and CP violation effects. A very large mass detector, of the order of 20 kton, can be constructed at the price of the order of 1 BSF. While this cost is probabbly comparable with the cost of construction of the neutrino factory itself, this detector would provide as complete a set of physics information as possible.

References

[1] E.Eskut *et al.*, Nucl.Inst. and Meth.A401,7(1997); see also: CHORUS collaboration, submitted to Lepton Photon 99, July 1999, hep-ex/9907015.

[2] MINOS Collaboration, Fermilab proposal P-915, NuMI-E-473, April 1999; see also R. Edgecock, these proceedings.

[3] Migliozzi, these proceedings.

[4] Burnett, T. H. *et al.*, NIM, **A251** , p.583, (1986).

[5] W.W. Armstrong *et al*, Atlas Technical Proposal.